Invited Paper

Multiple quantum well-based modulating retroreflectors for inter- and intra-spacecraft communication

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ABSTRACT

Free space optics (FSO) can provide high data rates with efficient use of power. However, small platforms may not be able to support the payload requirements of a conventional FSO terminal. An alternative FSO terminal uses a modulating retro-reflector (MRR). MRRs shift most of the power, weight, and pointing requirements to one end of the link. With a MRR configuration, it is possible to establish a two-way FSO link using a single laser transmitter. The MRR terminal of these systems can be small, lightweight, and low power. The MRR maintains the small beam divergence of a conventional optical communications link, but gains the loose pointing advantage of an RF link, reducing the pointing requirements. Communication needs in space present many asymmetric scenarios in which a MRR architecture could be beneficial. This paper describes some of the current capabilities and limitations of MRR systems, as well as applications to space links. An evaluation of the radiation tolerance of modulators is presented.

Keywords: Free-space optics, modulating retroreflector, multiple quantum well, radiation tolerance, FSO, MQW, MRR

1. INTRODUCTION

Free space optical communication has emerged in recent years as an attractive alternative to conventional RF techniques. Free space optics (FSO) can provide high data rates with efficient use of power due to its high directionality. Narrow beamwidths provide exceptionally high antenna gains that are beneficial to size, weight, and power. They also decrease susceptibility to interference between platforms. However, narrow beamwidths also require highly accurate pointing and tracking. Size, weight, and/or power of a high-quality pointing and tracking system can exceed that of the communications hardware. If a platform is small or has little available power, the requirements of a conventional optical communications link may be prohibitive.

An alternative to a conventional FSO terminal is a modulating retro-reflector (MRR). Using a MRR shifts most of the power, weight, and pointing requirements to one end of the link. This allows for asymmetric links between platforms with different capabilities. With a MRR configuration, it is possible to establish a two-way optical link using a single laser transmitter. Such systems can be lightweight and low power. Pointing requirements of the MRR are set by the field of view of the retro-reflector, generally about 10 to 20 degrees per retro-reflector. The retro-reflection is insensitive to platform jitter. Despite the very generous pointing tolerance, the retro-reflected beam has a divergence equal to the diffraction-limit of the retro-reflector (typically about 200 micro-radians). Thus the MRR end of the link maintains the small divergence of a conventional optical communications link, but gains the loose pointing advantage of an RF link.

Communication needs in space present many asymmetric scenarios in which a MRR architecture could be beneficial. MRRs open up FSO communications to platforms previously unable to use it, such as nano-satellites. Space provides a nearly ideal environment for FSO from an optics point of view, eliminating the problems of scintillation and atmospheric absorption. As a result, terrestrial systems which are currently in use should have significantly improved ranges in space.

2. MULTIPLE QUANTUM WELL MODULATING RETRO-REFLECTORS (MRRS)

A MRR couples a passive optical retroreflector such as a corner-cube or a cat's eye retroreflector with an electro-optic modulator. Figure 1 shows an unmodulated (CW) laser interrogating a MRR comprised of an absorptive modulator and a retroreflector. If the interrogation beam is within the retro-reflector's field of view, the beam will return to the interrogator with data impressed on it. Optical MRRs were demonstrated[1] before the invention of the laser, but were

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14. ABSTRACT
Free space optics (FSO) can provide high data rates with efficient use of power. However, small platforms may not be able to support the payload requirements of a conventional FSO terminal. An alternative FSO terminal uses a modulating retro-reflector (MRR). MRRs shift most of the power, weight, and pointing requirements to one end of the link. With a MRR configuration, it is possible to establish a two-way FSO link using a single laser transmitter. The MRR terminal of these systems can be small, lightweight, and low power. The MRR maintains the small beam divergence of a conventional optical communications link, but gains the loose pointing advantage of an RF link, reducing the pointing requirements. Communication needs in space present many asymmetric scenarios in which a MRR architecture could be beneficial. This paper describes some of the current capabilities and limitations of MRR systems, as well as applications to space links. An evaluation of the radiation tolerance of modulators is presented.

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restricted to short distances and low data rates. Recent advances in optoelectronic devices and FSO have greatly increased the capabilities of MRR systems. The Naval Research Laboratory has developed MRR systems using multiple quantum well modulators[2] for a variety of space as well as terrestrial applications. This discussion deals specifically with multiple quantum well (MQW) modulators. Various other modulator technologies have been used in MRRs and compared elsewhere[3].

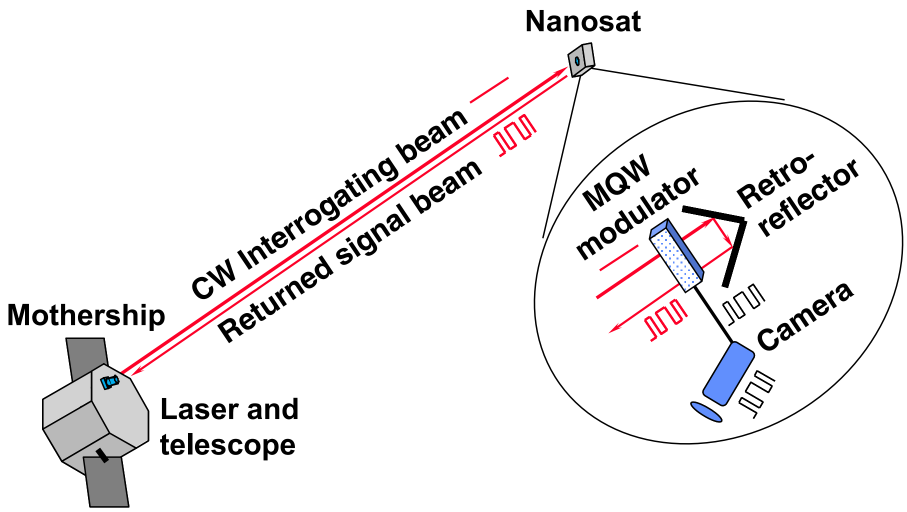

Figure 1: MRR system. Electrical signal is impressed onto the incident CW laser beam; data is returned to the interrogating satellite

2.1 Multiple Quantum Well Modulators

Since 1998 the Naval Research Laboratory has investigated modulating retroreflectors based on semiconductor multiple quantum well (MQW) electro-optic modulators[4]. These types of modulators have very high intrinsic switching times, and in practice are limited in their modulation rate only by *RC* time constant, where *R* is the electrical resistance and *C* is the capacitance. Thus the maximum modulation rate is determined by the device capacitance, which is related to the device area, and the lateral resistance, which is determined by the area as well as the electrode design. The design of an MRR link must balance using a large optical aperture to return sufficient light with the degradation in the *RC* time that comes with large area devices.

A MQW modulator is a PIN diode with multiple thin layers of alternating semiconductor alloys in the intrinsic region, as shown in Figure 2. These layers consist of a lower band-gap material, the well, and a higher bandgap material, the barrier. This type of modulator is attractive for modulating retroreflector applications because it can have a large area, and its modulation characteristics are essentially angular and polarization independent. Using InGaAs/AlGaAs MQW structures grown on GaAs substrates, operating wavelengths between 0.8-1.06 µm can be accessed[5]. Using InGaAs/InAlAs MQW structures grown on InP, the wavelength region around 1.55 µm can be accessed. The modulator is used in a surface-normal orientation to cover the aperture or focal area of the retroreflector. The distance the light travels through the active region is the thickness of the epitaxial layers, which is a few microns. A tradeoff between contrast ratio, optical transmission, tolerable capacitance, and available electronic drivers determines the number of quantum wells, and thus the thickness.

Because the semiconductor layers are very thin, the conduction and valence bands are quantized, and the exciton absorption feature at the band-edge becomes narrower in linewidth and enhanced in absorption. The center wavelength of the exciton is determined by the composition of the well material as well as the width of the well. When a reverse bias is applied across the MQW, the electric field changes the quantum well potential, shifting the exciton feature to the red and changing the magnitude of the absorption at any given wavelength. A modulating voltage on the quantum well is then converted into an optical amplitude modulation over about a 10 nm bandwidth, as shown in Figure 3.

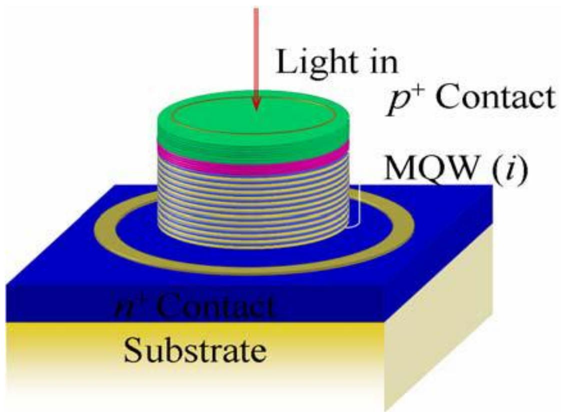

Figure 2: The layer structure of a MQW modulator

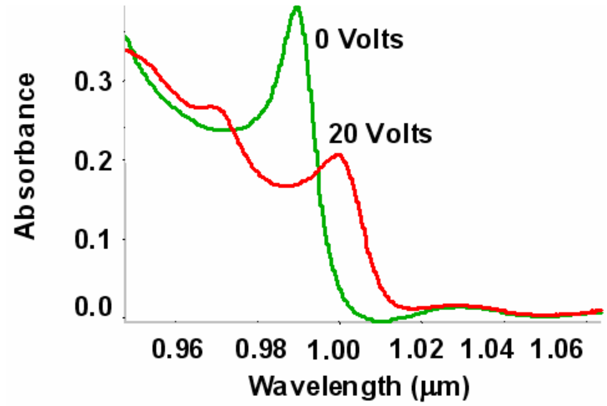

Figure 3 - Absorption spectra of large area MQW modulator for both 0 V and 20 V applied reverse bias

3. MRR LINKS

The link equation for MRR systems can be written as an extension of the conventional FSO equation. In addition to the transmitter and receiver terms, additional terms are included to account for the MRR's antenna gain, optical loss, and modulation efficiency. Because the light completes a round trip, atmospheric attenuation and free space range loss both appear twice. This free space range loss is highly significant for MRR systems, as it causes the optical power to fall off as $1/R^4$ instead of $1/R^2$.

The MRR acts as both a receiver and transmitter. It intercepts a portion of the light from the interrogator and retro-reflects it, and then acts as a transmitter aperture. Assuming the retro-reflector aperture is overfilled, the retro-reflector antenna gain is then the product of the transmitter and receiver antenna gains

$$G_{MRR} = \left[\frac{\pi D_{retro}}{\lambda}\right]^4 S \tag{1}$$

Where D_{retro} is the diameter of the retro-reflector aperture, λ is the wavelength of the light, and S is the Strehl ratio of the retro-reflector optic. As can be seen above, the gain has a fourth power dependence on the diameter of the retro-reflector. Since there is also a fourth power dependence on range, doubling the aperture of an MRR approximately doubles its range.

The optical modulator at the retro-reflector will have its own optical loss and contrast ratio, both of which affect the returned signal strength. These two parameters can be combined into one figure of merit, the modulation efficiency, defined as

$$M = e^{-\alpha_{On}} - e^{-\alpha_{Off}} = e^{-\alpha_{Off}} \cdot \left[C_{MQW} - 1\right] \tag{2}$$

where α_{On} and α_{Off} are the modulator's double-pass absorption in the on and off state respectively and C_{MQW} is the optical contrast ratio of the MQW.

Given an MRR's antenna gain and modulation efficiency, an MRR link can be expressed in terms similar to a conventional optical link as

$$P_{sig} = P_{Las} G_T L_T L_R T_{atm} G_{MRR} L_{MRR} M L_R T_{atm} G_{\mathrm{Re}c} L_{rec} \tag{3}$$

where P_{sig} is the retro-reflected signal power, P_{las} is the laser power, G_T is the optical antenna gain of the interrogator's transmit optics, L_T is the loss in the transmit optics, $L_{R,}$ is the free space range loss, T_{atm} is the atmospheric transmission, L_{MRR} is the optical loss of the MRR excluding modulator loss, G_{rec} is the optical antenna gain of the receiver on the interrogator, and L_{rec} is the optical losses in the receiver. Definitions of the conventional terms are given in reference 6.

The strong dependence of the MRR optical antenna gain on aperture motivates using a large aperture retro-reflector. As range is increased, larger apertures are required to make up for the free space range loss. For corner-cube based MRRs, the modulator diameter must equal the retro-reflector aperture. MQW modulators in particular are *RC* time limited. The capacitance is directly proportional to the area, so larger modulators are slower and more require more power.

It is possible to increase the data rate for a given modulator diameter by sub-dividing it into pixels as described in reference 1 and driving the pixels separately, but this does not decrease the power draw. This power consumption can become large for high data rates, and the heating it induces in the MQW may shift the peak operating wavelength and degrade the contrast ratio[11] of the modulator.

4. CAT'S EYE MODULATING RETRO-REFLECTORS

Given the scaling rules described above there is an obvious problem in achieving long range, high data rate MRR links. These links require high MQW modulation speed, driving one towards smaller modulators, while at the same time requiring a higher retro-reflected optical signal, driving one towards larger optical apertures. This is impossible for a corner-cube based MRR for which the modulator size must equal the optical aperture.

A class of optical systems called cat's eye retro-reflectors can overcome this problem if properly designed. There is no one form of cat's eye retro-reflector, but all contain some sort of focusing optics and a reflector. If the cat's eye MRR is to operate over a wide field of view, then optics f-number is important. A high f-number optic implies a large modulator in the focal plane. This is because the focal spot will move as the angle of incidence changes. The range of motion of the spot determines the modulator size,

$$D_{\mathrm{mod}} = f\# D_{retro}\theta_{retro} \tag{4}$$

where D_{mod} is the modulator diameter, $f\#$ is the f-number of the cat's eye and θ_{retro} is the FOV in radians that the cat's eye must work over. In order to keep the modulator small, the f-number should be as low as possible while still retaining diffraction-limited performance.

Even a sophisticated cat's eye optic will have an f-number of about 2. If the optic is to cover the same field of view as a corner-cube (about 0.5 radians) then $D_{mod} = D_{retro}$, the same situation as with a corner-cube. However, a cat's eye MRR can offer two advantages: If the required FOV is not large a cat's eye MRR can have a small modulator, whereas the modulator size for a corner-cube MRR is independent of the FOV. Second, while the focal spot does wander over a large area for a wide FOV, it only covers a small part of the focal plane at any one time. Thus if the angle of arrival can be determined, and if the modulator is divided into sub-pixels, then only a small part of the modulator needs to be driven at any one time, greatly reducing the power draw.

A benefit of the angle dependence of the focal point location is that it allows the MRR to act as either a transmitter or as an angle-of-arrival sensor. This same dependence was used to allow angle division multiplexing for multiple independent point to point links from a single telecentric cat's eye MRR[7].

There is no one type of retroreflector ideal for all MRR systems. Each variation has unique characteristics which may be beneficial or disqualifying in different situations. The retroreflector must be chosen based on the specific system for which it is intended. Corner-cube retroreflectors are best for highly asymmetrical links, where small size, light weight, or ruggedness are critical. These attributes also allow a large FOV to be created by arraying. A typical corner-cube retroreflector-based device has been demonstrated[8] with links up to 5 Mb/s at 1.6 km, yet the entire package containing modulator, corner-cube retroreflector, mount, window, and drive electronics weighs only 8.5 g (0.3 oz.). This same device has been used in a quincuncial array, increasing the FOV to 60 degrees. The array weighs 85.5g including all drive electronics. Such arrays have been used in links to a UAV[9] as well as to a boat moving at 15 knots. CERs are best for links requiring high data rates at long distance, but with less restriction on space, weight, and power. An aspheric curved focal plane CER MRR was used in a 7 km link at 45 Mb/s[10], and another modulator has demonstrated 70 Mb/s operation[11].

5. RADIATION EFFECTS

An important question about the use of such systems in space is the radiation tolerance of the MQW modulator. In most modulating retro-reflector systems the modulator must have optical access to the outside of the spacecraft, which limits

the amount of shielding that can be used. In a preliminary study irradiation using 20 MeV protons up to a total exposure level of 6.4 x 10^{10} protons cm^{-2} failed to show performance degradation of InGaAs/AlGaAs MQW modulators. To further investigate this question we examined the effects of proton irradiation on the most important characteristics of MQW modulators[12].

Three InGaAs/AlGaAs MQW modulators were subjected to a stepped bombardment of 1 MeV protons. Two of the modulators were unbiased during the irradiation; the third was at a 15V reverse bias during the irradiation. The reverse leakage (dark) current, optical contrast ratio, peak operating wavelength, and the absorption spectrum were measured for increasing radiation exposure levels.

5.1 Radiation levels tested compared to Low Earth Orbit exposure

It is important to put the levels of irradiation exposure into perspective in terms of radiation exposure levels typically encountered in the space environment. A low earth orbit is specifically chosen, as that is a primary target application for these MQW modulators. A circular 1,111 km orbit, inclined 60 degrees with respect to the Equator will be assumed. Applying the formalism of Summers, *et al.*[13], the proton radiation environment experienced by a GaAs-based device after one year in this orbit is equivalent to a value of displacement damage dose (D_d) of about 1.5x10^9 (MeV/g). This assumes a 25 μm thick glass (SiO_2) window covering the modulator. The 1 MeV proton fluences experienced by the QW modulators can be converted to D_d by multiplying by the appropriate value of nonionizing energy loss (NIEL), which is 0.5402 MeV cm^2/g in this case.

The results are shown in Table 1. The irradiation levels studied here are equivalent to many years in Earth orbit, indicating that the present experiments significantly over-tested the devices. This was purposefully done to ensure that all of the damage modes in the devices were exercised. Thus, the QW modulators will be expected to operate with essentially no degradation for the duration of a standard space mission. Furthermore, these devices can be expected to operate satisfactorily in more harsh radiation environments such as medium Earth Orbits (MEO). The cumulative fluence, equivalent displacement damage dose (D_d), and equivalent number of years in LEO orbit for each irradiation increment are shown in Table 1.

Table 1 - Comparison of irradiation levels of the present experiments with those experienced in Low Earth Orbit

Fluence (cm^{-2})	Equivalent D_d (MeV/g)	Equivalent number of years in LEO Orbit
8 x 10^{11}	4.32 x 10^{10}	28.0
4 x 10^{12}	2.16 x 10^{11}	140.2
4 x 10^{13}	2.16 x 10^{12}	1402
1 x 10^{14}	5.40 x 10^{12}	3,506
4 x 10^{14}	2.16 x 10^{13}	14,024

5.2 Measured effects of radiation

The reverse leakage (dark) current increased linearly with increasing particle fluence, as shown in Figure 4. The most likely mechanism for the dark current increase is radiation-induced point defects within the bulk GaAs material, which forms the *p-i-n* diode junction. These defects give rise to defect energy levels within the band-gap that act as trapping and recombination centers. The linear increase in dark current is a result of the fact that these defects are introduced linearly with increasing fluence.

The optical contrast ratio was relatively stable with irradiation, as shown in Figure 5. No degradation was observed until fluences higher than 10^{14} cm^{-2}, which has been shown to be an extremely high level of irradiation in comparison to the radiation environment in Earth orbit (Table 1). At the highest fluence level, there is a distinct decrease in contrast ratio; however the device continues to operate.

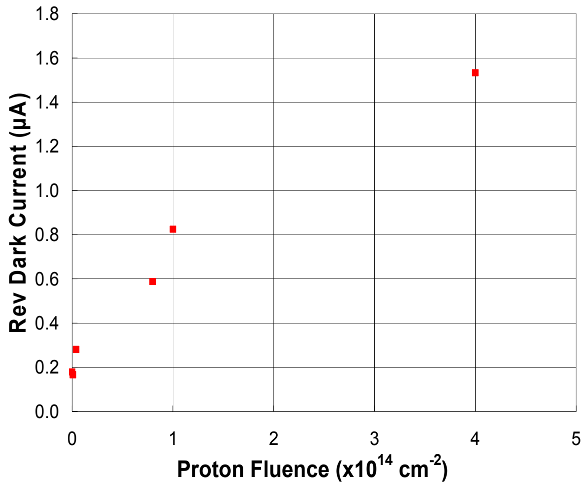

Figure 4 - Reverse leakage current measured at 20 V reverse bias after irradiation by increasing 1 MeV protons fluences. The data is seen to increase nearly linearly with fluence.

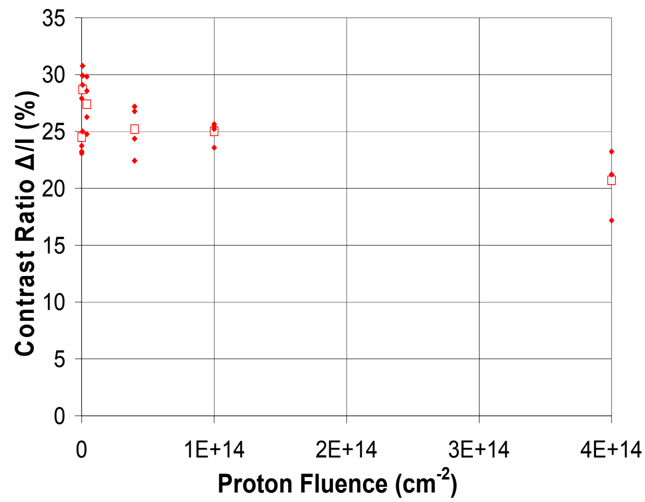

Figure 5 - Contrast ratio response to 1 MeV protons. Data for individual modulators are shown as points. Average values at each fluence level are shown as hollow squares.

The absorption spectra with the modulators reverse biased at various values were recorded after each irradiation using a Fourier Transform Infrared (FTIR) spectrometer. In Figure 6, the peak exciton wavelength of the MQW modulators is shown as a function of proton fluence. A significant shift in wavelength is only evident at the highest fluence level. The irradiation caused a slight decrease in the magnitude of the exciton absorption peak and a small shift of the peak to lower wavelengths. The exciton peak also appears to be somewhat broader after irradiation. Shown in Figure 7 is the difference in absorption spectra at 0 and 20 V applied reverse bias, measured before and after irradiation at a fluence of 10^{14} cm^{-2}.

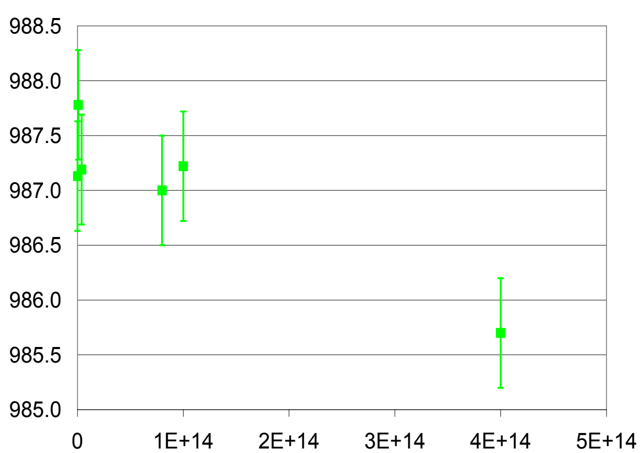

Figure 6: Effect of 1 MeV protons on peak exciton wavelength of MQW modulators. X-axis is proton fluence in cm^{-2}, y-axis is wavelength in nm.

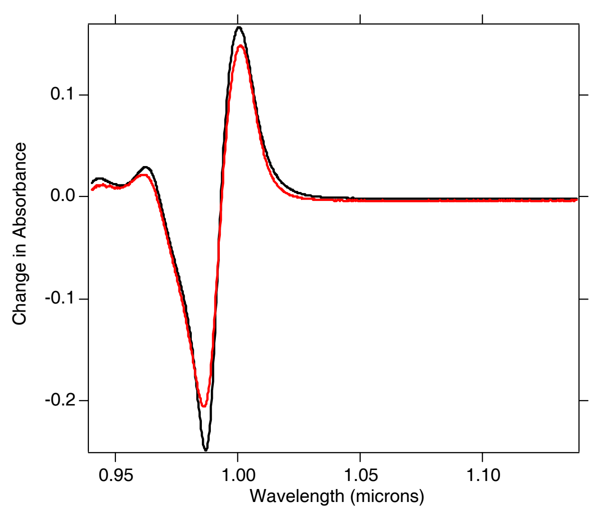

Figure 7: Effect of 1 MeV Protons on the absorption spectrum. Black = before exposure; Red = after 10^{14}/cm^2 protons.

5.3 Significance of radiation effects on MQW modulator and system link budget

Although this semiconductor epitaxial structure is similar to that of semiconductor light emitting diodes (LED), laser diodes, and photodiodes, its electrical operation is quite different. LEDs and laser diodes are operated under forward

electrical biases, with the majority of the current in the device flows from *p*-contact through the intrinsic layer and out the *n*-contact. In contrast, MQW modulators act as a capacitor, with large AC current flow onto and off of the capacitor plates, but minimal current through the device. Photodiodes also operate under reverse bias, but they are much more sensitive to reverse leakage (dark) current than MQW modulators.

In contrast to the above devices, none of the observed degradations have a major impact on the modulator or system performance. The reverse leakage current increased by a factor of 9 to 1.5 μA. This is a significant increase, however the drive current for the same modulator requires is approximately 60 mA with each cycle, so even highly degraded reverse leakage currents are not a problem. We routinely operate similar modulators with a reverse leakage currents of tens of microamps with no noticeable penalty. The degradation in contrast ratio, which decreases the Modulation Efficiency *M* term of Equation (3), would add less than 1 dB of loss to the overall link budget. This would cause a decrease in maximum range on the order of 10%, depending on the particular link. The broadening of the excitonic peak which comes with the decrease in contrast ratio actually somewhat increases the operating temperature range. The slight shift in wavelength is within the normal operating range, and would not require any compensation if enough margin is built into the system. If desired, the wavelength shift could be compensated for with temperature control or with a tunable laser source.

5.4 Difference in radiation response of InGaAs/InAlAs coupled well modulators

These radiation experiments were carried out on InGaAs/AlGaAs square well modulators. We have since changed our standard modulator structure to an InGaAs/InAlAs coupled well structure[2]. With the change in materials, we might expect to see a difference in radiation behavior. Being a smaller bandgap, a larger dark current and larger radiation-induced increase in dark current is expected. However, as discussed above, our operational parameters are fairly insensitive to radiation effects. In particular, dark current increases are not very significant to the operation of the modulators. Displacement damage effects may be more significant in the InGaAs/InAlAs devices but are still expected to be a very small. Charge trapping and dopant neutralization (carrier removal) effects are typically the displacement damage effects of primary concern. Charge trapping reduces the minority carrier diffusion length, but the MRR operation is nearly insensitive to this. Carrier removal in III-V materials typically converts *p*-type material to *n*-type, but experimental measurements will be required to confirm this for InGaAs/InAlAs system. In any event, some of the stability in contrast ratio appears to have benefited from carrier removal effects in our InGaAs/AlGaAs modulators. As can be seen from the data, the contrast ratio actually increased after the first and second irradiation steps before decreasing, which could be attributed to carrier removal. Subsequent measurements of capacitance with similar devices supported this view.

6. APPLICATIONS IN SPACE

Several potential applications in space have been investigated to take advantage of the asymmetry allowed by the MRR architecture. Both corner-cube retroreflector and cat's eye retroreflector MRRs have potential applications. If extremely loose pointing requirements are required, arrays of corner-cube retroreflector MRRs would be most appropriate. To cover 360 degrees with a single axis of rotation, 12 MRRs would maintain a signal level at least 50% of a single MRR at normal incidence. If full spherical coverage is needed for a satellite with no attitude control, high index of refraction corner-cubes would increase the field of view, such that no more than 30 MRRs would be needed for omni-directional coverage. Based on the weight and power draw of our current corner-cube based MRRs capable of several km links, the total weight of devices plus drive electronics would be less than 300 g, with total power draw on the order of 250 mW at 1 Mb/s. Power draw would decrease approximately linearly with data rate if lower data rates are acceptable.

Cat's eye retroreflector MRRs could be used if a long distance is required with high data rate. These MRRs are heavier and more complex, so they would only be appropriate in situations where there is less difference in size, weight, and power capacity between the two platforms.

One possibly scenario for MRR systems would be in planetary exploration. Data could be returned to a central base station from a variety of small, low-powered data collectors, as shown conceptually in Figure 8. Naval Research Laboratory MRRs were used in a demonstration of this type of architecture on a Mars Rover testbed[14].

Several specialized space applications have been investigated at the Naval Research Laboratory, which are significantly different from typical terrestrial MRR applications. These include using MRRs serving dual roles, either for both a communication link and for ranging, or both as a transmitter and receiver.

Two separate approaches to use MRRs as dual-use devices for both optical communication and navigation aids were demonstrated. In one approach, an array of eight MRRs was placed on the target spacecraft platform[15]. Each MRR was modulated with a unique code sequence, allowing for individual discrimination of the returned composite signal from a single photodetector on the pursuer platform. A beam from the pursuer platform illuminated the array of MRRs. The target's relative position vector and aspect angles were derived from the relative intensities of the modulated signal returns from each retroreflector on the target array. Signal discrimination was achieved by passing the aggregate photon return through a set of matching filters tuned to each unique retroreflector modulation code. Utilization of MQW corner-cube retroreflectors enabled the target array to be populated with devices that require only milliwatts of power, are light and compact, and are radiation hard. The sensor system provided high-bandwidth optical communication, centimeter-level relative positioning, and arc-minute-level relative orientation of the target platform with minimal sacrifice in target size, weight, and power. Experimental results using a dual-platform, multi-degree-of-freedom robotics testbed provide verification and demonstration of the concept, highlighting its potential for applications such as interspacecraft rendezvous and capture, long-baseline space interferometry, and formation flying.

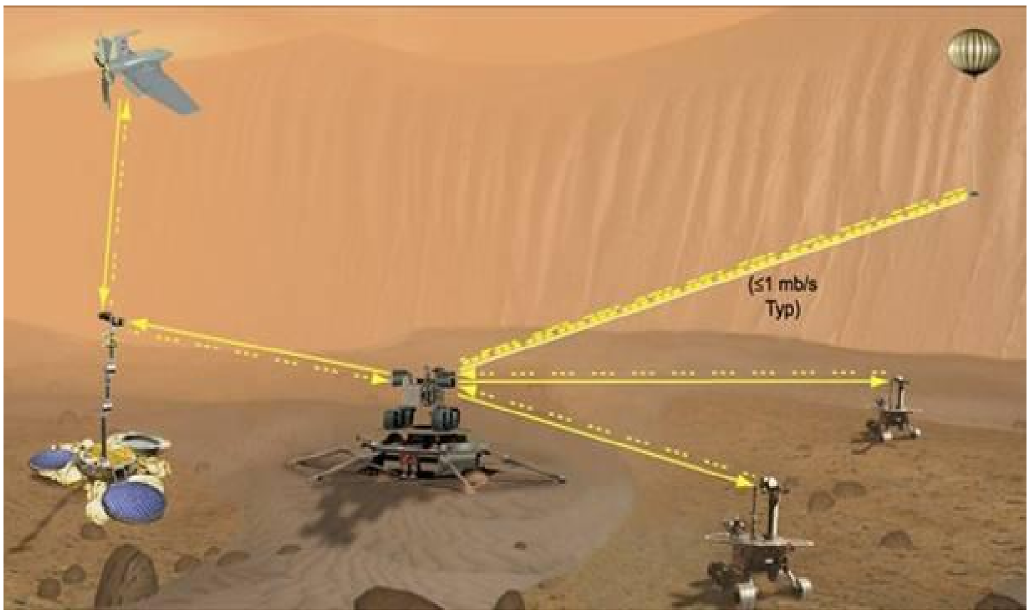

Figure 8: Artist's conception of central data collection using MRRs

A second approach included the use of time-of-flight for ranging along with optical communication. An array of five MRRs was located on the target spacecraft[16]. Spacecraft navigation information was determined by using the MRR array to impose five distinct modulation frequencies on the optical transmit beam, and analyzing the received signal on the pursuer spacecraft to extract target attitude and range data, while simultaneously establishing an interference-free communication channel between the target and pursuer spacecraft. The interrogator was adapted for simultaneous ranging and video transfer using the modulating retroreflector laser communication link. The interrogator demonstrated ranging accuracy on the order of a few mm. To the best of our knowledge, this was the first report of simultaneous ranging and data transfer over an optical link.

Another use envisioned for MRRs in space would be for optical tagging to identify remotely located consumables or other objects[17]. The work demonstrated that a tag could be identified out of a crowded environment. The method allowed additional information, such as geolocation or container content, to be sent with alternating data streams without affecting acquisition.

A very different use of cat's eye MRRs did not use the asymmetry property of the system, but rather the angular dependence of cat's eye modulators. The purpose was to create a free-space optical implementation of MIL-STD-1553 for intra-spacecraft communication[7]. Free-space optics could eliminate the mass and moment of inertia of traditional wiring harnesses, allow higher data rates, allow insertion of new instruments without new cabling, and is inherently insensitive to RF interference. Because the MQW modulators use a *p-i-n* structure, the same device was used both as a modulator for transmitting data and as a photodiode for receiving data. This was demonstrated with three MRRs. The

angular dependence allowed multiple simultaneous bidirectional links between MRRs, with beams from different directions being focused on different pixels in an array. Each pixel operated as both a photodetector and as a modulator. Two-way communication between a single MRR and two identical MRRs were accomplished simultaneously with the first reported use of the angle division multiplexing capability of cat's eye MRRs.

7. POTENTIAL RANGE IN SPACE WITH CURRENT TERRESTRIAL SYSTEMS

Space systems will have much in common with systems already developed for terrestrial use. It is important to note the current state of the art, as well as point out the differences between the space environment and MRR systems used in the atmosphere.

The most advanced terrestrial system reported to date is a 7 km, 45 Mb/s marine link from ship to shore using a cat's eye modulating retroreflector with a 5 W laser[10]. The link budget is shown in Table 2. The system operates with a link margin of 6-8 dB, in part to account for scintillation effects which are not present in space. Atmospheric transmission losses which account for 3 dB of loss for the round trip are also not present in space. Taking these into account, the same system operating in space would have an additional 10 dB in the link budget. Applying this additional margin to the range loss would allow -220 dB in each direction. This results in a comparable range in space of 12 to 13 km with no changes to our current system.

Table 2: State-of-the-art 7 kilometer terrestrial cat's eye link budget

Term	Parameter	Formula	dB
Transmit Power	5 Watts	Measured	37 dBm
Transmitter loss		Measured	-1.0
Transmitter antenna gain, Gaussian beam underfilling transmit aperture	Full angle e^{-2} divergence θ_{div} = 300 microradians	$\frac{32}{\theta_{div}^2}$	85.5 dB
Range loss (interrogator)	Range, R = 7 Km λ = 1550 nm	$\left[\frac{\lambda}{4\pi R}\right]^2$	-215.1
Atmospheric transmission	16 km visibility		-1.5
MRR Modulation efficiency, M	Coupled-well modulator	$e^{-\alpha_{Off}} \cdot \left[C_{MQW} - 1\right]$	-7.5
MRR loss	Loss due to anti-reflection coating	Measured	-0.7
MRR T/R Antenna gain, G_{retro}	D_{retro} = 1.6 cm S = 0.4	$\left[\frac{\pi D_{retro}}{\lambda}\right]^4 S$	177
Range loss (retro return)	7 Km	$\left[\frac{\lambda}{4\pi R}\right]^2$	-215
Atmospheric transmission	16 km visibility		-1.5
Receiver antenna gain	D_{rec} = 15 cm	$\left[\frac{\pi D_{rec}}{\lambda}\right]^2$	108
Receiver loss	Fiber coupling loss		-1
Predicted received power	0.28 μW		-35.5 dBm
Actual received power	0.4 μW		-34 dBm

With only minor changes, the current system could be used at even longer ranges. The above calculations ignore the potential of using smaller beam divergences in space. Due to the effects of scintillation, our current terrestrial system uses a beam divergence on the laser of 300 microradians in order to ease pointing requirements. Without scintillation, a beam divergence of 30 microradians would be reasonable. This would add an additional 20 dB to the link. If this is added to the above effects, the allowable range loss would be -230 dB in each direction, comparable to a range in space of approximately 39 km.

The above calculations were done with a cat's eye MRR with a G_{retro} of 177 dB. If such high data rates are not needed, a 1 cm corner-cube retroreflector could be used with a link budget penalty of approximately 7 dB. This would allow a simpler, smaller, lighter, and lower power system to be used at ranges in the low 10's of km.

8. CONCLUSIONS

FSO communication using the MRR architecture is quite well-suited to the space environment. The asymmetric nature of MRR links corresponds with the situation in space, where platform often have different power and weight budgets, and many platforms are extremely limited in these areas. MRRs are extremely low in power, size, and weight, as well as being very radiation tolerant. Altering MQW modulator materials and designs are unlikely to cause any significant problems with radiation tolerance because of the electrical operation of these devices, although further studies would be prudent to investigate the carrier removal effects in particular. Space provides a nearly ideal environment for FSO from an optics point of view, eliminating the problems of scintillation and atmospheric absorption. Several possible applications have been presented.

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